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A. Kinkhabwala et al.

Soft X-ray Spectroscopy of Seyfert 2 Galaxies

A. Kinkhabwala, M. Sako, E. Behar, F. Paerels, S. M. Kahn

Columbia University, 550 W. 120th St., NY, NY 10027

A. C. Brinkman, J. S. Kaastra, R. van der Meer

SRON, Sorbonnelaan 2, 3548 CA, Utrecht, The Netherlands

D. A. Liedahl

Physics Department, LLNL, P.O. Box 808, L-41, Livermore, CA 94550

Abstract. Soft X-ray spectroscopy of Seyfert 2 galaxies provides perhaps the best method to probe the possible connection between AGN activity and star formation. Obscuration of powerful radiation from the inferred nucleus allows for detailed study of circumnuclear emission regions. And soft X-ray spectroscopy of these regions allows for robust discrimination between warm gas radiatively-driven by the AGN and hot collisionally-driven gas possibly associated with star formation. A simple model of a (bi-)cone of gas photoionized and photoexcited by a nuclear power-law continuum is sufficient to explain the soft X-ray spectra of all Seyfert 2 galaxies so far observed by the *XMM-Newton* and *Chandra* satellites. An upper limit of $\sim 10\%$ to an additional hot, collisionally-driven gas contribution to the soft X-ray regime appears to hold for five different Seyfert 2 galaxies, placing interesting constraints on circumnuclear star formation.

1. Introduction

Emission from warm, recombining gas has been shown to be a key feature of the soft X-ray emission from Seyfert 2 galaxies (Sako et al. 2000, Ogle et al. 2000, Sambruna et al. 2001). In Fig. 1, we show the *XMM-Newton* Reflection Grating Spectrometer (RGS) spectrum of the brightest Seyfert 2 galaxy, NGC 1068 (Kinkhabwala et al. 2001a). The presence of multiple radiative recombination continua (RRC) provide definitive evidence for a dominant recombining gas component with temperature $T \simeq 3\text{--}5$ eV. Recombination alone, however, is insufficient to explain all of the observed X-ray emission from these objects.

2. Model of Radiatively-Driven Gas Cone

We propose a model for the X-ray emission from Seyfert 2 galaxies consisting of a (bi-)cone of gas irradiated by a nuclear power-law continuum. (The nucleus –

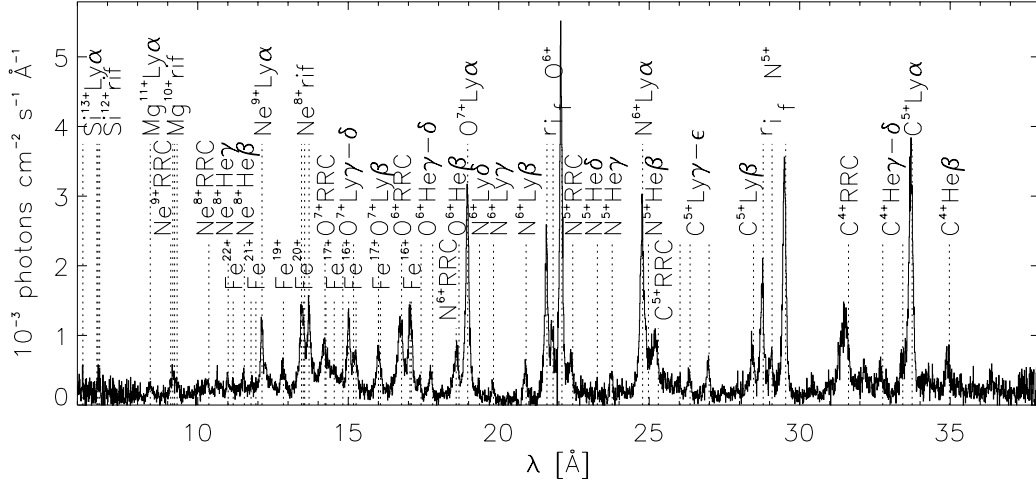


Figure 1. *XMM-Newton* RGS spectrum of NGC 1068. Note the bright RRC, strong forbidden lines in the helium-like triplets of oxygen and nitrogen, and relatively-strong higher-order transitions (labelled β , γ , δ , etc. up to the RRC). All of which are unambiguous signatures of warm photoionized and photoexcited gas (Sako et al. 2000).

located at the tip of the cone – is obscured along our particular line of sight.) We specify a single ionic column density, N_{ion} , and gaussian velocity distribution, σ_v , both *along* the cone. σ_v is chosen to be consistent with observations of broadened line absorption in soft X-ray observations of Seyfert 1 galaxies, where values from ~ 200 km/s (Kaastra et al. 2000) to ~ 600 km/s (Sako et al. 2001) have been found. We note that σ_v may be due to a superposition of multiple velocity components. A broadening of the observed lines due to a separate gaussian velocity distribution along our particular line of sight (probably unrelated to the velocity distribution along the cone) is also taken.

The upper right panel in Fig. 2 shows the expected spectrum of the helium-like O VII ion. The panels on the left show the “Seyfert 1” view down the axis of the cone in absorption, and the panels on the right show the “Seyfert 2” view in reemission for column densities in O VII from 10^{16} to 10^{19} cm $^{-2}$. All photons absorbed out of the power-law continuum in the left panel are reprocessed and reemitted in the right panel. Further details of our model can be found in Kinkhabwala et al. (2001a) and Behar et al. (2001).

3. Model Fits to Seyfert 2 Galaxy Spectra

Our model works remarkably well for explaining the bulk (and possibly all) of the X-ray emission from NGC 1068. Fig. 3 shows our fit to lines associated with transitions in O VII for the RGS spectrum shown in Fig. 1. Similarly, in Fig. 4, we show fits to the previously published *Chandra* HETG spectra of two other Seyfert 2 galaxies. We find that the claimed observation of hot collisionally-driven gas in NGC 4151 of Ogle et al. (2000) was premature, and we verify the earlier conclusions for Markarian 3 of Sako et al. (2000), who claimed that photoionization and photoexcitation in addition to a scattered power-law continuum were sufficient to explain its observed X-ray spectrum.

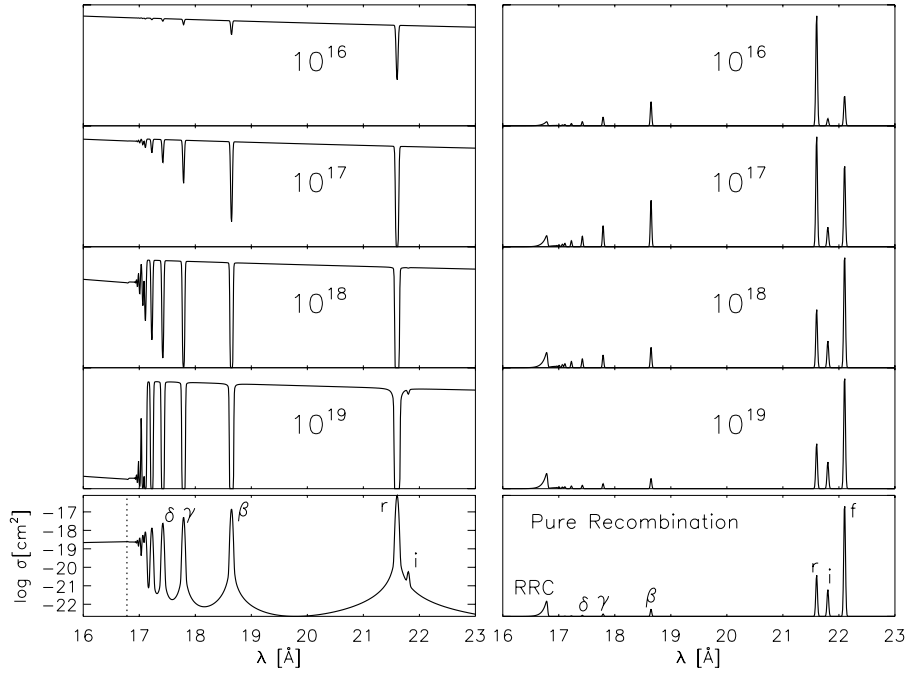


Figure 2. Effect of varying column density ($N_{ion} = 10^{16} - 10^{19} \text{ cm}^{-2}$) along the cone to absorbed (“Seyfert 1” view on the left) and reemitted (“Seyfert 2” view on the right) spectra for O VII. For “Seyfert 2” view, note the varying relative strength of resonant transitions to pure recombination emission (bottom right panel). ($\sigma_v = 200 \text{ km/s}$ with linear, but arbitrary vertical scales for flux.) Bottom left panel gives cross section for photoexcitation/photoionization with separating boundary.

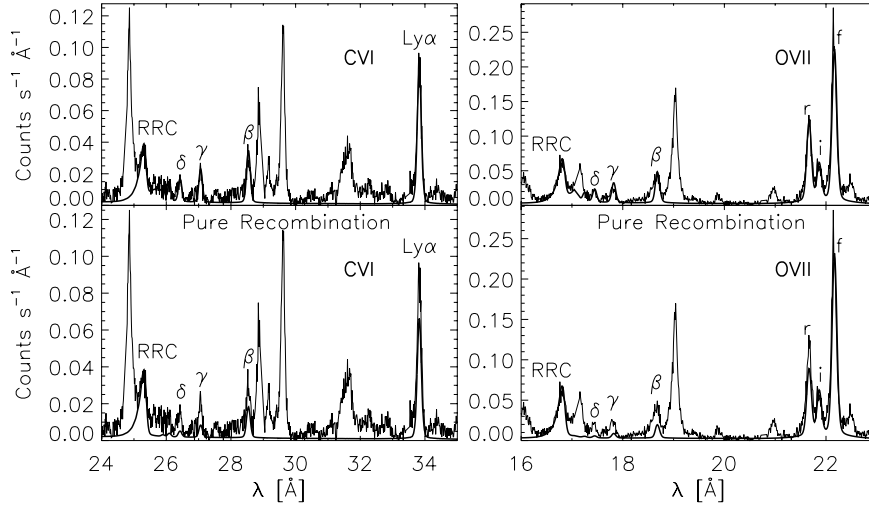


Figure 3. Fits to C VI and O VII for RGS spectrum of NGC 1068 ($\sigma_v = 200 \text{ km/s}$ along the cone and $N_{ion} = 10^{18}$ for both ions). Bottom panels show recombination alone, demonstrating presence of significant photoexcitation. For C VI fit, a factor-of-two reduction of photoionization relative to photoexcitation was taken for a better fit (possibly due to absorption by N VII $\text{Ly}\alpha$ shortward of the C VI RRC).

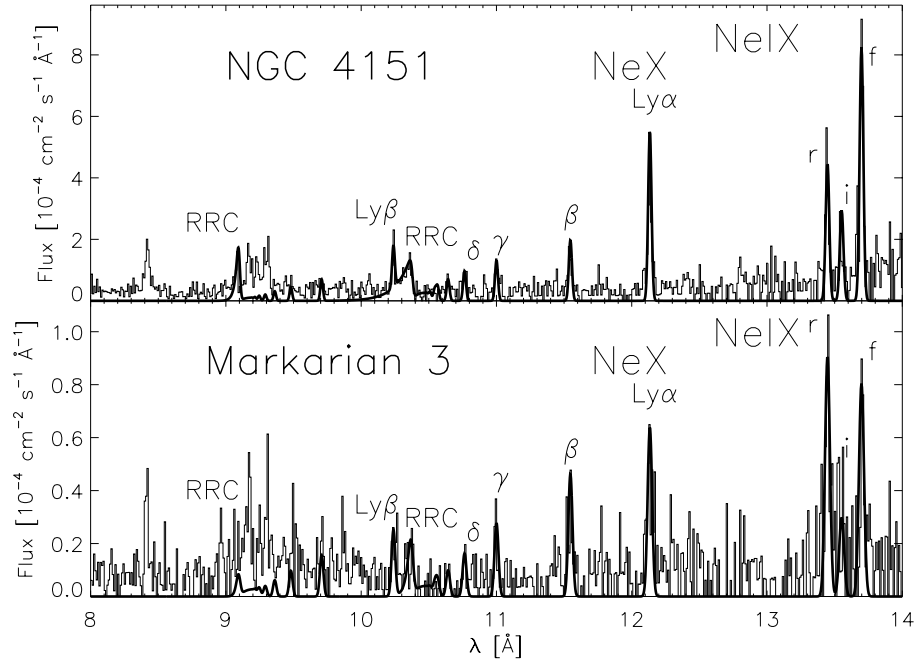


Figure 4. *Chandra* HETG spectra of NGC 4151 and Markarian 3. Spectral differences are mostly due to differing Ne IX and Ne X column densities (e. g., Fig. 2) of 2×10^{18} and $3 \times 10^{18} \text{ cm}^{-2}$ for NGC 4151 and 5×10^{17} and $1 \times 10^{18} \text{ cm}^{-2}$ for Markarian 3 (using $\sigma_v = 200 \text{ km/s}$).

We estimate an upper limit of $\sim 10\%$ of the soft X-ray emission may be due to hot, collisionally-driven gas in NGC 1068. Preliminary analysis of *Chandra* HETG spectra of four other Seyfert 2 galaxies (Markarian 3, NGC 4151, Circinus, NGC 4507) suggests that their remarkably similar spectra are also dominated by reprocessed AGN emission, with a similar upper limit to a hot collisional gas component. This places interesting limits on the amount of star formation in their circumnuclear environments (Kinkhabwala et al. 2001a,b).

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